HIGH POWER THYRATRON EVALUATION*

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ABSTRACT

Evaluation of high power thyratrons designed and fabricated by IT&T and EEV for SDIO applications will be discussed. Results will be presented on switches for burst mode applications and continuous duty operation. For burst mode conditions of interest for LLNL's LINAC programs IT&T's F259 and F266 and EEV's CX 1547, 1547(R), and 1536(R) were evaluated at pulse repetition rates up to 6 kilohertz at peak forward voltages of 25 and 40 kilovolts. The feasibility of EEV's CX 1700 type thyratrons to switch up to 1 megawatts in a continuous mode of operation was also explored. In the latter study, conducted at a repetition rate of 100-200 hertz, the peak current was 18 kiloamperes and the peak forward voltage was 40 kilovolts.

INTRODUCTION

Previous high average current investigations of hydrogen thyratrons (1, 2) have been at low repetition rates and with the adiabatic mode of operation. Currently, SDIO is supporting research and development studies at both IT&T and EEV that will lead to super power switching capability on a continuous duty basis (3). A potential application for such high power switch tubes is the linear induction accelerator that has been developed at Lawrence Livermore Laboratories (4). To meet the average current and run time objectives, it is planned to use multiple state-of-the-art thyratrons connected in parallel. It is also anticipated that the SDIO thyratron R&D program, for which the Phase III objective is 500 amperes, will eventually result in a switch that will significantly reduce the number of devices required.

One of the features of the new U.S. Army Pulse Power Center (PPC) is the availability of high power test and evaluation facilities, not only for use by DoD but available for use by other Government agencies and commercial organizations as well. Table 1 lists the facilities and their capabilities for both burst and CW operation. Systems 1A, 1B, 2, and 3 are used in these studies. Figure 1 is a photograph of some of the experimental test beds in one of the two High Bays available at the PPC. A capacitor test facility is at the left of the picture and thyratron test beds are to the right.

SDIO and Lawrence Livermore National Laboratory (LLNL) are utilizing the facilities to evaluate the state-of-the-art thyratron feasibility at average and root mean square currents that are 5-7 times greater than current ratings. Figure 2 shows thyratrons that have been evaluated at the PPC for the LLNL application. The F-259 and F-266 are the direct results of the Phase I and II SDIO effort at IT&T. These tubes are designed for oil immersion and have dispenser type cathodes. The dispenser emitter can handle average current densities that are 5-10 times higher than conventional oxide-coated emitters thereby allowing significantly smaller sized cathode and envelope designs for high power switching.

The overall effort is divided into the following areas:

I. Evaluate medium voltage thyratrons to establish feasibility and reliability of operation at 25 and 40 kilovolts at up to 6 kilohertz for on times of up to 100 seconds.

II. Evaluate the capability of high average power thyratrons to continuously operate at one megawatt of average power.

EVALUATION

The general scope of the evaluation was specified by LLNL and SDIO and the requirements are summarized in Table 2. Results obtained on each task are given below.

Task A: For Task A a line type modulator is used in which the network (PFN) is made up of seven pulse forming networks, each having a 14 ohm impedance connected in parallel. The pulse width is a nominal 5 microseconds and the total PFN capacitance is 1.35 microfarads. The 2.3 ohm load is obtained by circulating a water-copper sulfate-sulfuric acid solution between copper electrodes. A 200 gallon tank containing a water cooled coil is used to contain the liquid. Multiple charging inductors are available for use in combined series-parallel arrangements to adjust the recharge voltage waveform. A charging diode is included. An ignitron is used as a diverter in the event of a fault in the thyratron. The dc power supply is capable of an output of 22 kilovolts at 160 amperes for 60 seconds every ten minutes using the burst mode of operation or 1.4 megawatts for continuous operation.

Electrical characteristics of the 4 ohm facility are given in Table 3a and the 55 ampere operating condition. The peak forward voltage is 25 kilovolts and Tektronix 6015 voltage probes are used to monitor the anode, gradient grid voltage, and control grid voltages. Pearson current transformers monitor the charging and anode and grid currents. Luxtron fiber optic coupled temperature probes are used to monitor temperature at several selected points on the tube. Use of fiber optics permit attaching the probes to the high voltage electrodes in oil. Waveforms of the pertinent voltages and currents are used as inputs to Tektronix 7612D digitizers, and a PDP 11 computer is used to monitor and analyze the experimental results.

An EEV CX 1547, CX 1547(R) and an IT&T 259 were evaluated in Task A. The CX 1547(R) had a more massive auxiliary electrode but in all other aspects it was identical to the 1547. Triode structures, which the 1547 and 1547(R) are, in many ways, better suited for high repetition rate operation. Gradient grid tubes such as the IT&T F259, F266, and the EEV 1536(R) do not have a balanced grid construction resulting in a non-uniform capacitance distribution. At low repetition rates a resistance divider of 10 to 20 megaohms per gap is used to obtain equal voltage division during the voltage charging period. For the high frequency operation of interest to this study, external capacitors are used to obtain the balanced voltage distribution.

Task A: EEV CX 1547 Results: Generally speaking, the thyratron required very little preliminary aging in the test modulator. One to two hours of operation at 30 kilovolts at 1 to 2 amperes of average current followed by a half dozen 100 seconds runs at 25

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kilovolts -20 amperes and at 25 amperes were all that was required. Evaluation runs were then methodically logged. A tabulation of the results is given in Table 4. In order for a run to be counted as OK, it had to be free of pre-fires, missed pulses, kick-outs, and the change in anode delay time had to be less than 100 nanoseconds. Preliminary testing of the first CX 1547 was done without negative grid bias on grid number 2, and the cathode and reservoir heaters were connected in parallel with 6.0 volts applied. However, starting with the 40 ampere-100 second runs, a negative dc bias of 135 volts was applied to grid number 2, the auxiliary current to grid number 1 was increased from 50 to 150 milliamperes, and the cathode and reservoir heaters were separately controlled. The 6.0 volts was applied to the cathode heater and 6.3 volts to the reservoir heater. These changes were recommended by H. Menown of EEV and reliability was considerably improved by the changes.

An initial 114 runs were made on the 1547 which are not included in this paper. Reliability was significantly improved when the auxiliary circuit charges discussed above were incorporated. Over ninety consecutive runs were then logged without a failure at average currents of 40 to 47 amperes. Table 4(a) shows this latter data only. During the 100 seconds runs at 47 amperes, an inverse discharge to grid 2 occurred at 60 seconds into the run. At this time, TAD increased, pre-fires and kick-outs became more frequent, and testing was terminated on this thyratron. It may have been possible to extend the 1547 operating limits by reducing the magnitude of the negative grid bias on G_2 but at the time, it was decided to evaluate the 1547(R).

Task A: EEV 1547(R) Results: As previously stated, the 1547(R) was identical to the 1547 except for the use of a much more massive G_2 structure. Its operation in the 4 ohm modulator is summarized in Table 4(b). Average current capability of 55 amperes for 100 second run times was demonstrated. Out of 250 runs at average currents ranging from 30 to 55 amperes, there were 10 runs which terminated. In Table 5, the probability of an unsuccessful event occurring is shown for the 40, 47, and 55 ampere tests on the 4 ohm system. This data suggests that the reliability of the 1547(R) was improving with operating life.

Task A: IT&T 259: Results obtained on the IT&T F259 are given in Table 4c. This thyratron performed without a failure for 26 runs at which time the auxiliary electrode shorted to the cathode. It was not possible to trigger the device after that and it was returned to IT&T for analysis. Cause of failure was found to be a defective weld.

Task B: The schematic for the RLC modulator is shown in Figure 3. The energy storage capacitor C_N is 0.35 microfarads and the load, RL, is identical to that used on the line type modulator except that the copper sulfate-sulfuric acid solution is adjusted to obtain a 4.3 ohm load. An inductor, L_D, of 6 microhenries was used in the discharge circuit to give an under-damped condition.

It was originally thought that a command resonant charge circuit would be necessary to operate at the repetition rates of interest to LLNL. It was established that for both the IT&T and the EEV thyratrons operation at up to 6 kilohertz could be obtained using a conventional resonant charge circuit. All measurements obtained with the RLC modulator were done with resonant charging with the circuit components adjusted to give the under-damped condition. Characteristics of the Task B RLC modulator are shown in Table 3b for a pulse repetition rate of 6.2 kilohertz.

Task B: CX 1547(R) Results: Results obtained using the CX 1547(R) are summarized in Table 4c. The improved reliability observed at the end of the 55 ampere testing on the 4 ohm facility was not observed in the RLC tests. Reliability was improved by increasing the off time. Generally speaking, the first run of the day was completed without problems. However, reliability was poor unless there were several hours between operations.

Task C: Task C evaluation was conducted using an RLC modulator similar to that shown in Figure 3. Circuit components were selected to give the under-damped condition and the objective pulse width. Both the IT&T F266 and the EEV CX 1536(R) were tested for 10^7 pulses. Both tube types are gradient grid devices and both use a dispenser cathode. Measured parameters for the test are summarized in Table 4c. Performance of the CX 1536(R) was considered excellent. Pre-fires, missed pulses, and kick-outs were not detected. Inverse clipping was not seen. In the case of the IT&T F266 four pre-fires were detected. On two occasions the modulator kicked-out. During these tests the waveforms were recorded with a VCR. Play back of the waveforms did not provide information as to the cause of the shut downs.

For comparison, measured and calculated discharge current waveforms are shown in Figure 4. The calculated discharge current is obtained from the classic RLC solution for the under-damped case.

The measured current waveform was reproduced from an oscilloscope trace obtained using a current transformer. The parameters used for the calculation of current were taken from Table 4c.

Task D: Feasibility tests were conducted using the IT&T F266 and the EEV CX 1536(R) thyratron. The purpose of these experiments was to determine if 6200 hertz pulsing could be obtained at 40 kV using conventional resonant charging. Using a C_N of 0.27 microfarads and operating for short bursts, 15 seconds or less, charging of the capacitor was varied by changing the charging inductor Lc. Satisfactory operation at peak voltages up to 39 kV was obtained for recharge times as short as 168 seconds corresponding to a resonant charging frequency of 5950 hertz. At the operating frequency of 3000 hertz, used in the experiment, the average current measured 36 amperes. The charging inductor, Lc, was 13 millihenries and the rest of the circuit parameters were in Table 4c.

On the basis of this result it was decided to conduct the Task D evaluation using a conventional resonant charge circuit thereby significantly simplifying the test bed.

Task D: Testing: To conduct the Task D tests as called for in the LLNL Plan several changes were made in the modulator. The capacitor C_N was reduced to 0.125 microfarads and the discharge inductance L_D was made equal to 4.4 microhenries. The liquid load was increased to 6.7 ohms and a 25 millihenry charging inductor was used for Lc. Table 4d summarizes the circuit parameters and measured discharge characteristics.

Preliminary tests have been made on both the EEV 1536(R) and the IT&T F266. Both tubes have operated at the objective levels except that the operating repetition rate has been restricted to frequencies considerably less than the 6.2 kilohertz recharging frequency.

Task E: Phase A: The EEV CX 1700 HAH is a high power gradient grid thyratron containing a hollow anode design. The hollow anode design allows the switch to operate with up to 50% current reversal. Table 6 summarizes the ratings assigned by EEV to the tube and the ultimate levels at which SDIO wants the device evaluated at the PPC. A schematic of the test circuit designed to meet the SDIO objectives is shown in Figure 5. It is planned to test in two phases where the first phase testing will be conducted at a total circuit impedance of 2 ohms. In the second phase a one ohm circuit will be used.

For burst mode pulsing the system is designed to take advantage of adiabatic operation with run times limited by the heat capacity of the components. However, for the CX 1700 test bed continuous operation at 1 to 2 megawatts of average power is required which results in heat dissipation being significant in all of the components. To achieve the continuous operation objective the system design incorporates four PFN's which have each demonstrated operation at one megawatt of average power for a 2 minute burst mode in the past. For Phase A two pulse forming networks (PFN's) connected in tandem are then paralleled with a similar pair to produce a 40 kilovolt, 1 ohm, 10 microsecond line. A load assembly containing over 1300 ohmweave resistors cooled by a 40 horse power blower replaces the burst mode liquid loads. The CX 1700 must be operated in oil and an oil tank socket has been specifically designed for this test. Dissipation in the tank is substantial. The 1700 requires over 1800 watts of heater power and dissipation in the device associated with switching is estimated to be as high as 300 watt/dc ampere adding another 15,000 watts at the one megawatt test level. To maintain the ambient oil temperature at acceptable levels, the oil tank design includes a system to recirculate the oil through an oil to air heat exchanger. Part of the cooled oil from the heater exchanger is directed into the base of the CX 1700 via a shower head design and the balance of oil is directed up and through the radiators located on the exterior envelope of the thyratron. A small secondary pump taps the tank and passes the oil through a filter and then into the anode cooling pipe at a rate of 1.4 liters/minute.

Table 4e summarizes the initial modulator characteristics and measurements.

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Table 1
High Power Facilities

System	Voltage Kilovolts	Current Amperes	Average Power Megawatts	Burst Duration Seconds
1 (A)	22	160	3.3	60
			1.4	CW
1 (B)	22	160	3.3	60
			1.4	CW
1 (A) + (B)	22	320	6.6	60
			2.8	CW
2	20	400	8.0	20
			0.8	CW
3	37	30	1.0	CW
		50	1.5	60
4	22	80	1.7	20
5 (A)	125	4	0.5	CW
		8	1.0	120
5 (B)	125	4	0.5	CW
		8	1.0	120
5 (A) + 5 (B)	250	4	1.0	CW
		8	2.0	120
CHIP (1)	4 @ 3.1 kV	160	2.0	20
CHIP (2)	4 @ 3.1 kV	160	2.0	20

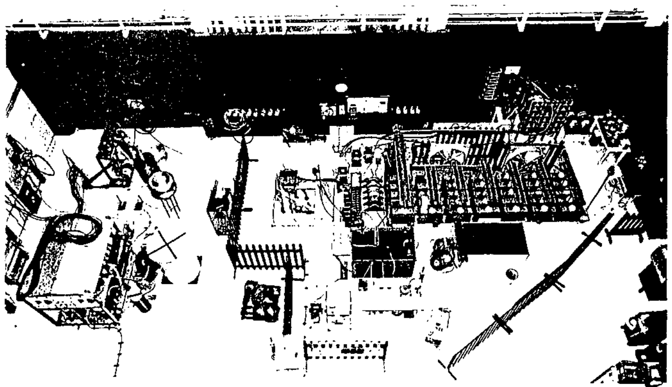


Figure 1 - High Bay Laboratory. Capacitor test bed on the left and thyratron test facilities on the right.

Table 2
Test Objectives and Requirements

	A	B	C	D	E
Peak Forward Voltage (kv)	25	25	40	40	40
Capacitance (µf)	1.35	0.35	0.25	0.125	0.25
Discharge Time (µs)	5	6	4.75	3	3
Repetition Rate (khz)	1.65	4.7	0.1	6.2	6.2
Burst Length (sec)	30,60,100	30,60,100	Cont.	15,30,60,100	15,30,60,100
Energy per Pulse (kj)	0.420	0.110	0.2	0.11	0.2
Average Power (kw)	500	680	20	660	1200

Table 3
Measured Test Parameters

	a	b	c	d	e
Peak Forward Voltage (epy in kV)	25.00	25.00	40.00	40.00	40.00
Peak Forward Current (i_b in kA)	5.80	3.00	4.80	3.45	18.00
Pulse Width (t_b in µs)	5.50	1.00	4.75	3.10	11.00
Average Current (I_{ave} in A)	55.00	55.00	1.10	--	40.00
Root Mean Square Current (I_{RMS} in A)	565.00	370.00			850.00
Capacitance (C_N in µf)	1.35	0.35	0.27	0.125	5.00
Load (R_L in Ω)	2.30	4.30	5.40	6.70	1.05
Network Impedance (Z_N in Ω)	2.00				1.05
Inductance (L_D in µh)		6.00	4.40	4.40	330.00
Pulse Repetition Rate (prr in khz)	1.645	4.70	0.10	5.95	.20

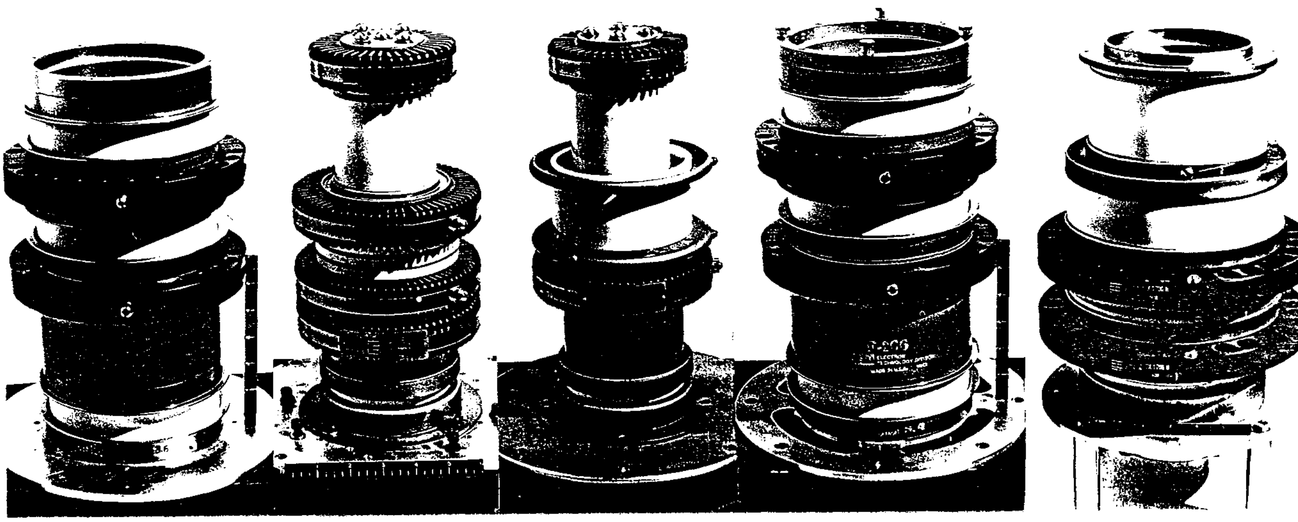


Figure 2 - Thyratron left to right; F259, CX1547, CX1536R, F266, CX1700H

Table 4

Summary of Test Results for Task A and B

Table	Task	Tube	Iave Amp	IRMS Amp	prr hz	Run Time Sec	Runs #	Failures #
4a	A	CX-1547	40	480	1140	100	25	0
			47	522	1435	30	25	0
						60	25	0
						100	25	3
4b	A	CX-1547R	30	425	840	100	25	0
			40	480	1140	30	25	0
						60	25	0
						100	25	6
			47	520	1370	30	25	2
						60	25	0
						100	25	0
			55	565	1635	30	25	1
						60	25	1
						100	25	0
4c	A	F-259	30	435	925	30	11	0
						60	10	0
						100	5	0
4d	B	CX 1547R	35	325	3515	30	19	5
						60	19	8
			55	375	4700	30	48	20

Table 5

Probability of a Non-Satisfactory Run for EEV 1547R in 4 Ohm Modulator

Iave A	Run Time Sec	# Satisfactory Pulses x 10^6	# Unsatisfactory Pulses	Probability of Failure
40	30	0.86	0	
	60	1.70	0	11×10^{-7}
	100	2.85	6	
47	30	1.03	2	
	60	2.06	0	3.1×10^{-7}
	100	3.40	0	
55	30	1.20	1	
	60	2.45	1	2.6×10^{-7}
	100	4.10	0	

Figure 3

RLC Modulator

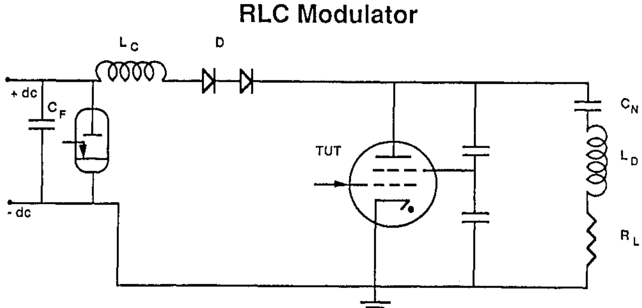


Figure 4

Measured and Calculated i_b

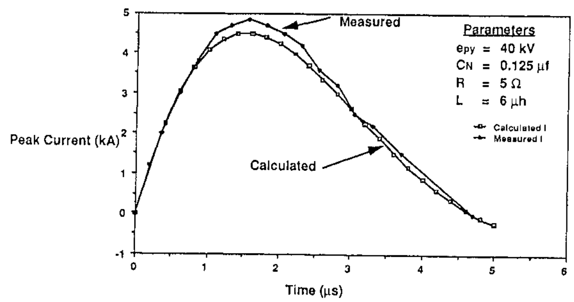
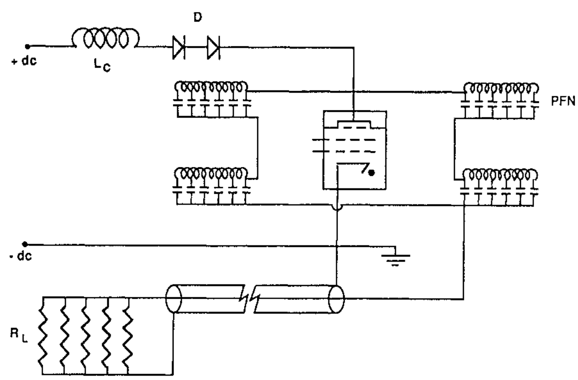


Figure 5

Megawatt Average Power Test Facility



Tabie 6

CX1700HAH Ratings and SDIO Objectives

Peak Forward Voltage kV	70	40 - 50
Peak Forward Current kA	50	40
Average Current A	50	50 - 80
Average Power MW	NR*	1 - 2
Peak Inverse Current kA	25	25
Pulse Width µs	NR*	5 - 10

* NR Not Rated